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Radiochemistry for NIF Implosion Diagnostics

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Acknowledgments

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Outline

- Brief review of indirect drive Point Design implosion characteristics.
- Examination of one specific, potential failure mode – X-ray drive asymmetry.
  - Success and failure implosion output comparison
  - Refractory material tracers Ir and Sc
  - Charged particle reactions 18O(α,n)21Ne and 79Br(d,2n)79Kr as diagnostics
- Preliminary conclusions
  - Viable diagnostic signatures for asymmetric failure modes
  - Hydrodynamic instability signature but detectability issues remain

The basic requirements for ICF igntion are quite straight forward

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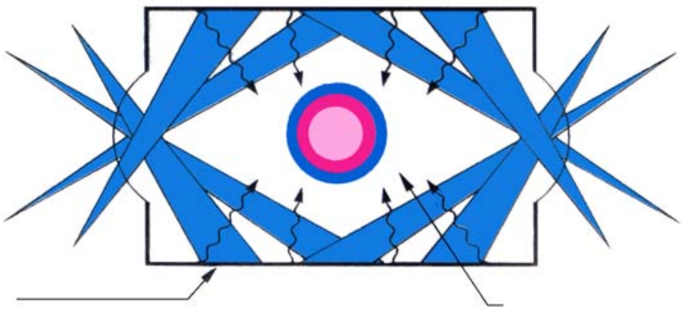
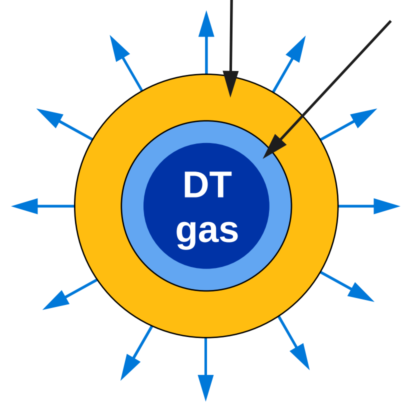
Laser driven high-z hohlraum

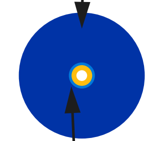


Capsule with Low-z Ablator for efficient absorption



Cryogenic fuel for efficient compression

Cold, dense main fuel (~1000 g/cm^3 with ρr = 1-2 g/cm^3)



Hot spot (10 keV with ρr = 0.2-0.3 g/cm^3)

Efficient x-ray production and symmetry adequate for a near spherical implosion

Spherical ablation to achieve high implosion velocity while suppressing instability growth

Near spherical collapse of the shell to produce a central hot spot surrounded by cold, dense main fuel

The NIF point design has a graded-doped, beryllium capsule in a $U_{0.75}Au_{.25}$ hohlraum driven at 300 eV

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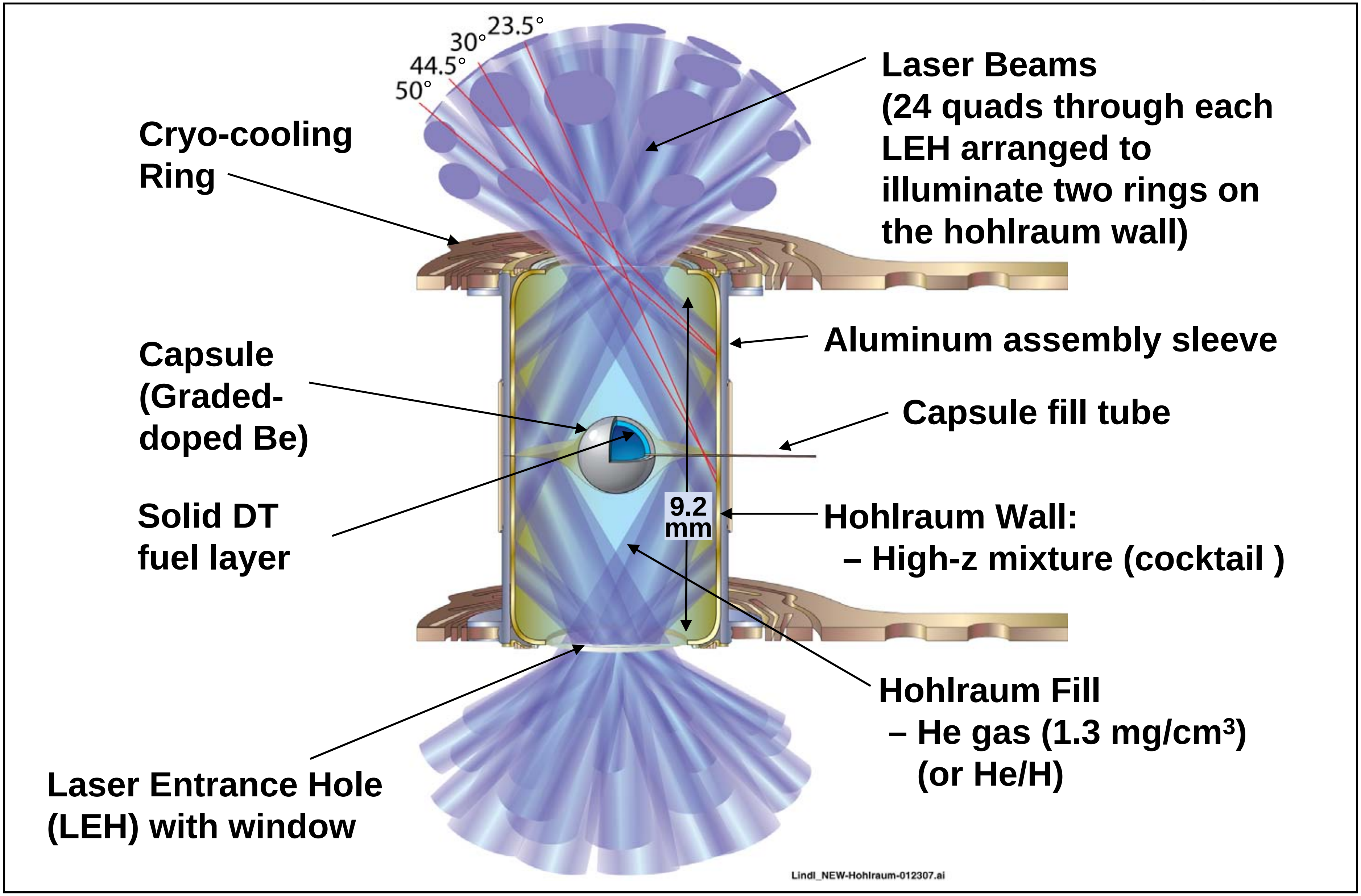


Ignition Campaign Overview

- Both hohlraum and capsule designs are carefully optimized with constraints imposed by laser drive performance.
- Separate pre-ignition experimental campaigns will isolate and resolve the major technical difficulties expected.
  - Laser-plasma interactions
  - Capsule performance
  - Laser-hohlraum issues
  - Laser pulse shaping/shock timing
- If the optimized, integrated configuration does not achieve ignition, failure diagnosis and recovery will be essential.

Failure Mode Diagnostics

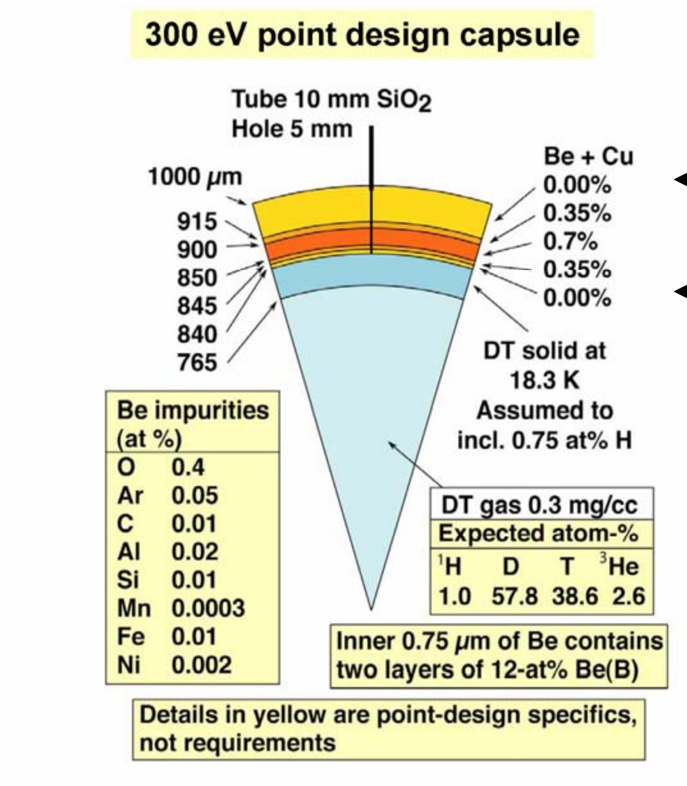
- Reliable, robust ignition diagnostics will be necessary to distinguish among possible failure modes.
  - Neutron time-of-flight
  - X-ray backlighting (ARC)
  - X-ray self-emission
  - X-ray and γ bang time
  - Neutron imaging
- Determination of excessive cold shell material mixing into the DT region remains a difficult problem.
  - Radiochemical tracer techniques?
  - Refractory or gas products?

Radiochemistry for Failure Modes

- *Motivation*
  - Purported advantages include inherent sensitivity to burn time conditions, energy-downscattered flux, and multiple “lines of sight” .
  - Investigate the feasibility of radiochemical tracers for failure mode signatures, especially asymmetric x-ray drive and mix.
- *Methodology*
  - Two-dimensional radiation-hydrodynamic simulations based upon the optimized Point Design capsule and x-ray drive.
  - Asymmetric drive failure modeled by varying the modal content of the optimal drive – typically a Legendre mode present in the drive.
  - Hydrodynamic instabilities induced by increasing the shell roughness beyond its specified limits.
  - Tracer materials (uniformly) loaded into the innermost shell region for maximal particle exposure.
  - Post-process to obtain product/(loaded tracer) ratios that might usefully distinguish among failure modes.

Single Shell Point Design

X-ray drive asymmetry (indirect drive)



Instabilities seeded by outer shell roughness

Tracer material loaded here for maximum particle flux
e.g. Ir, Sc, I, Br, ^{18}O

Instabilities seeded by inner shell roughness

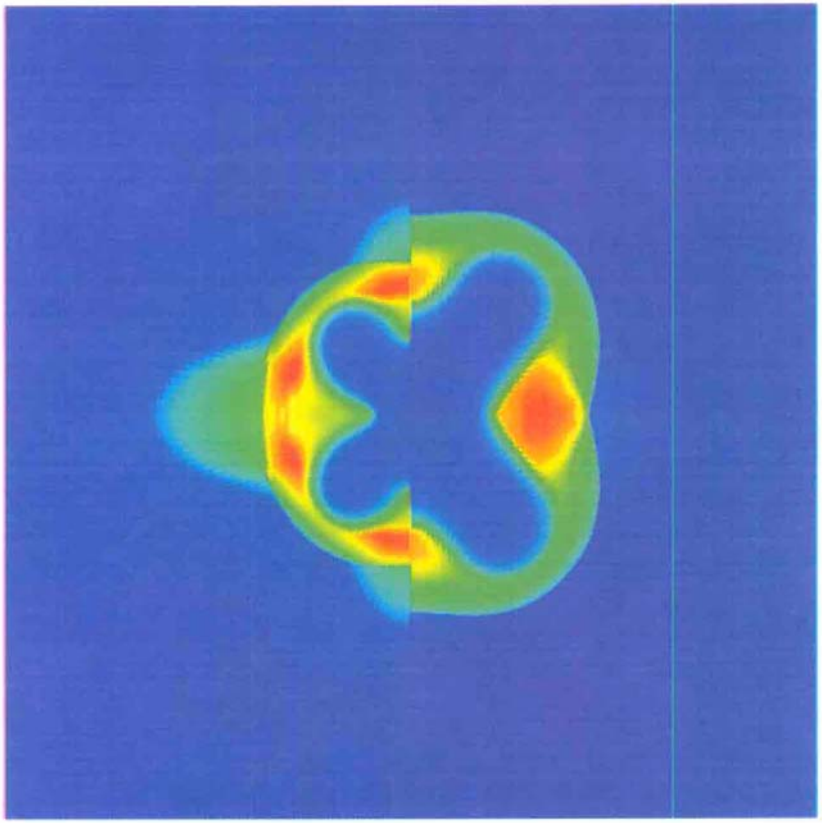
Anatomy of a Failure

- A common feature of failed (non-igniting) implosions is the relatively high time-averaged ρ-r since rapid expansion of the shell is suppressed.
- Differences in dense material distribution and hot spot geometry will affect tracer nuclear reactions.
- In the following example, the P_4 Legendre mode present in the drive was increased until the capsule performance was degraded to a yield of 1 MJ. This yield threshold, though not optimal, is still considered to be successful.
- A "hard" failure was also simulated by increasing the mode's amplitude by a factor of 1.5 producing yields in the range 50-100 kJ.

Negative P_4

$t_{peak} - t_{fwhm}/2$

Material Density

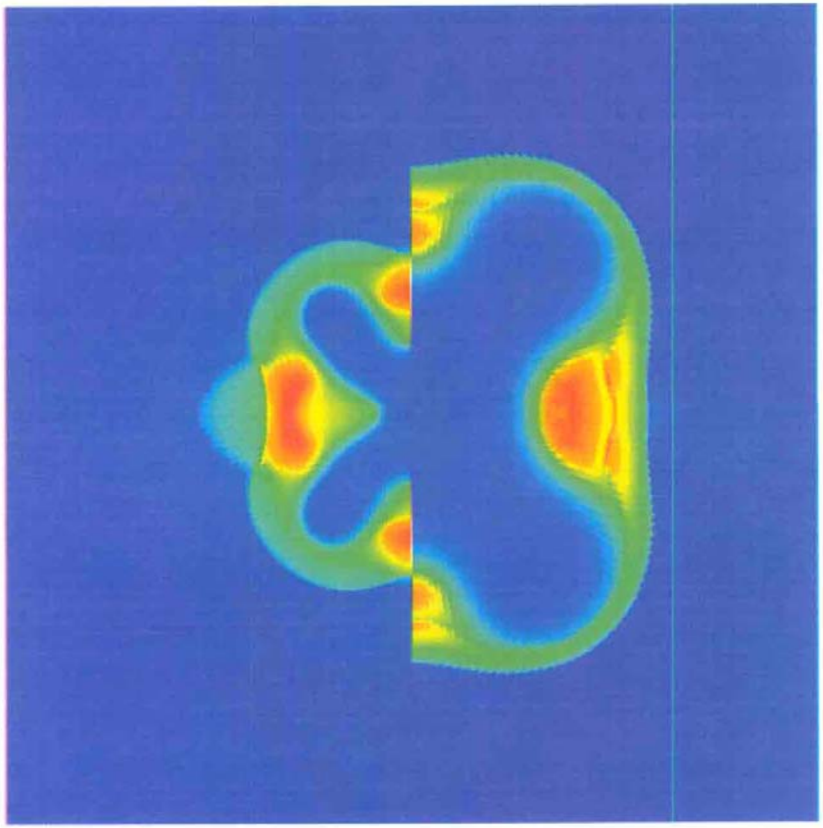


Failure **1 MJ**

Negative P_4

t_{peak}

Material Density

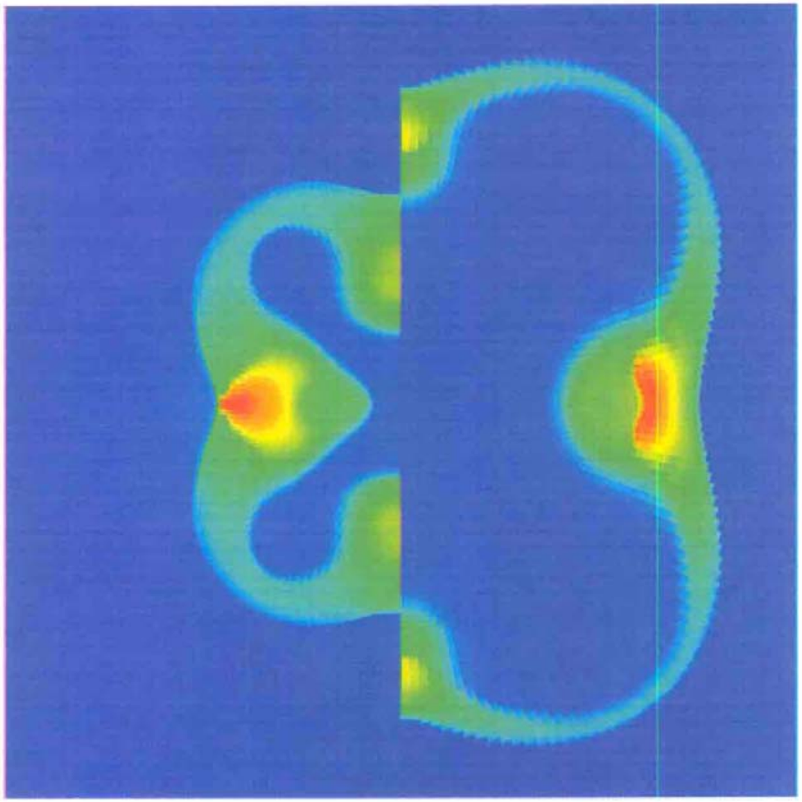


Failure **1 MJ**

Negative P_4

$t_{peak} + t_{fwhm}/2$

Material Density



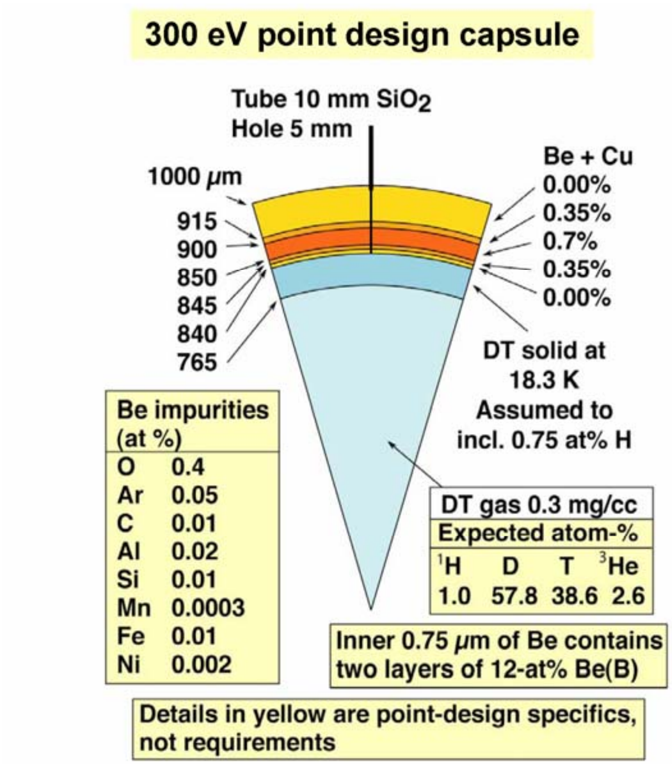
Failure **1 MJ**

Negative P_4 Output Comparison

	Failure	*Success*
Yield (MJ)	**0.048**	**3.42**
$N_{fraction}$ (E < 10 MeV)	**0.181**	**0.095**
$N_{fraction}$ (6 < E < 10 MeV)	**0.058**	**0.030**
NeutronNumber (12 < E < 17 MeV)	**1.41E+16**	**1.11E+18**
$N_{fraction}$ (22 < E MeV)	**2.2E-5**	**1.9E-5**
Total Neutron Number	**1.76E+16**	**1.25E+18**
ρ-R (time-weighted) (gm/cm^2)	**0.94**	**0.58**
γ fwhm (psec)	**74**	**38**
T_{ion} (keV)	**5.5**	**16.7**
Peak Offset (psec)	**-35**	**26**

Negative P_4/Ir-Loaded

P$_4$ asymmetry imposed



Ir, ^{18}O or I loaded
Capsule performance unaffected

Both igniting and hard failure cases simulated.

Post-processing produces
reaction product abundances

Ir Loading Example

- Natural abundance ^{191,193}Ir loaded into the innermost region of the ablator shell.
- Determine reaction products based upon a given cross-section network for different asymmetric drives.
- Example: ^{194}Ir
  - 1.45E+09 atoms produced for 3.42 MJ conditions (A_1)
  - 6.04E+07 atoms produced for 48 kJ conditions (A_2)
  - Scale the product atom numbers by the yields

$$(A_1/N_1) * (N_2/A_2) = (A_1/A_2) * (N_2/N_1) \approx (A_1/A_2) * (Y_2/Y_1)$$

In this case, there is a relative ratio of 3.37 which is a clearly measurable difference between the different drive conditions. The number of atoms is also acceptably large for detection.

Charged Particle Diagnostics/Asymmetric Drive

- Simplicity of inert gas collection on the NIF motivates the selection of these tracers.

- Detectable signals from both ^{21}Ne and ^{127}Xe.

- Evaluate the atom number ratios scaled by the yield
  - Ne atoms in high and low yield cases:

4.66E+9 2.64E+6

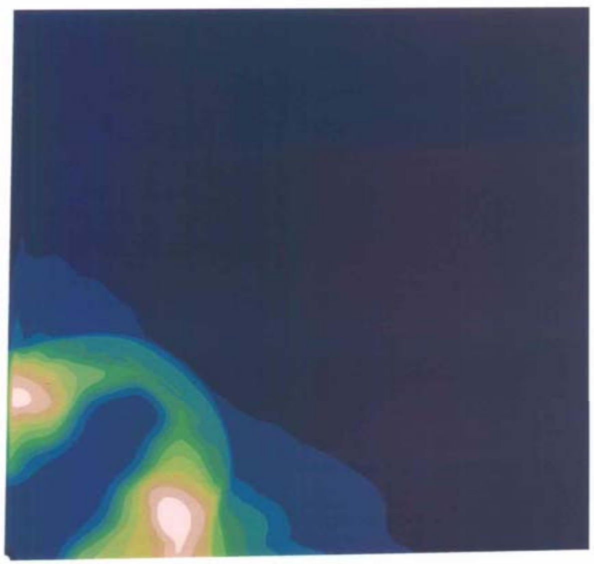
$$(A_1/A_2)*(Y_2/Y_1) = 24.8$$

  - ^{127}Xe atoms in low and high yield cases:

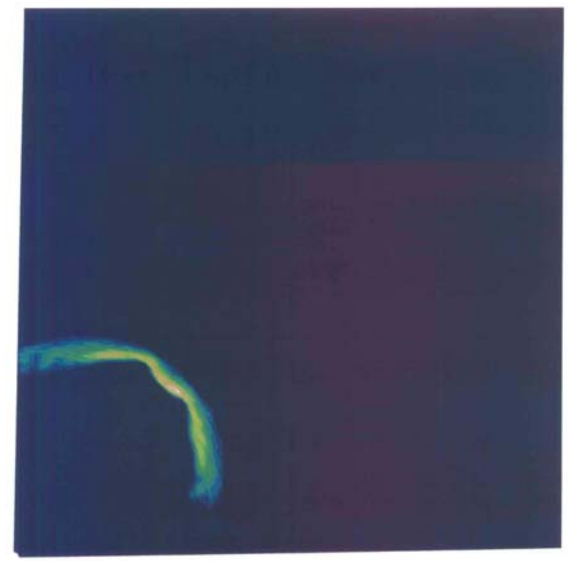
4.28E+8 1.32E+6

$$(A_1/A_2)*(Y_2/Y_1) = 4.55$$

Negative P_4 ^{21}Ne Evolution



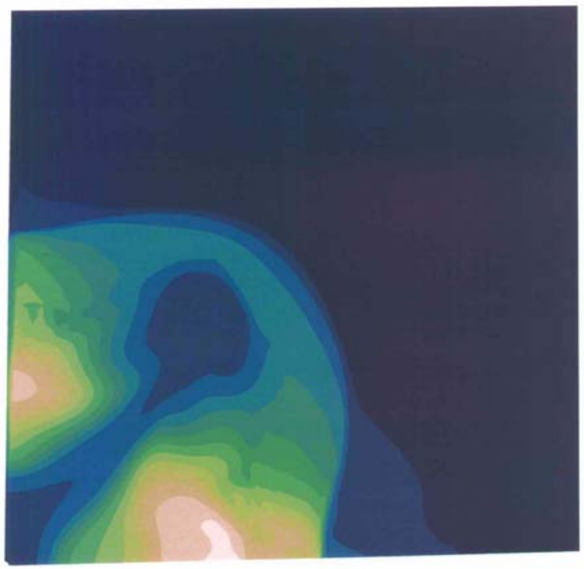
Density



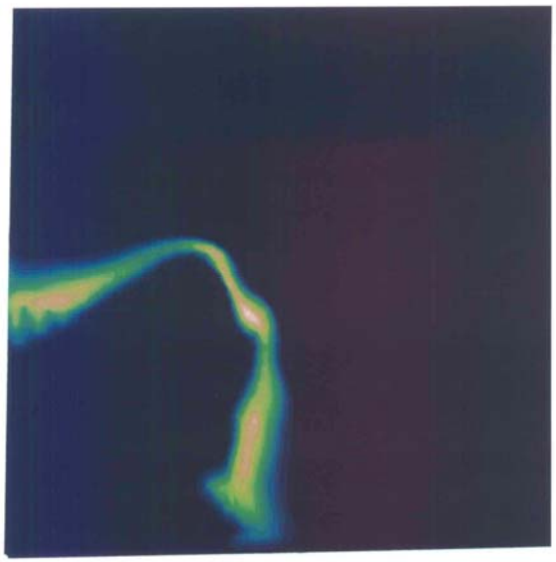
^{21}Ne Abundance

t_{peak} (psec)

Negative P_4 ^{21}Ne Evolution



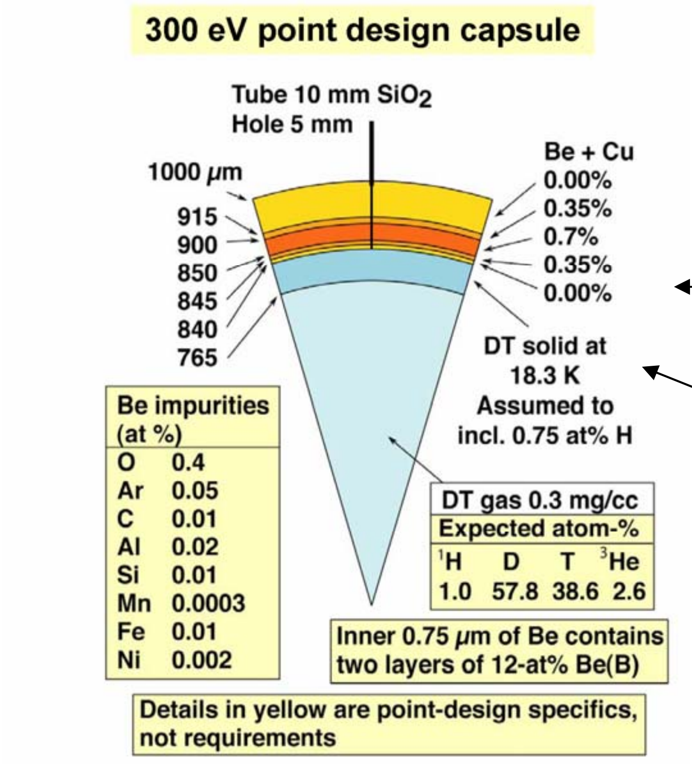
Density



^{21}Ne Abundance

t_{peak}+100 (psec)

Ice Roughness/^{18}O-Loaded



^{18}O, Br or I loaded
Capsule performance unaffected

Inner surface roughness imposed

Both igniting and hard failure cases simulated.

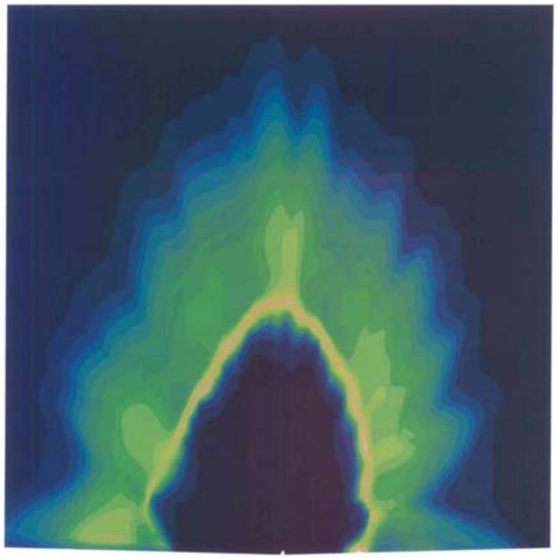
Post-processing produces
reaction product abundances

Charged Particle Diagnostics/Ice Roughness

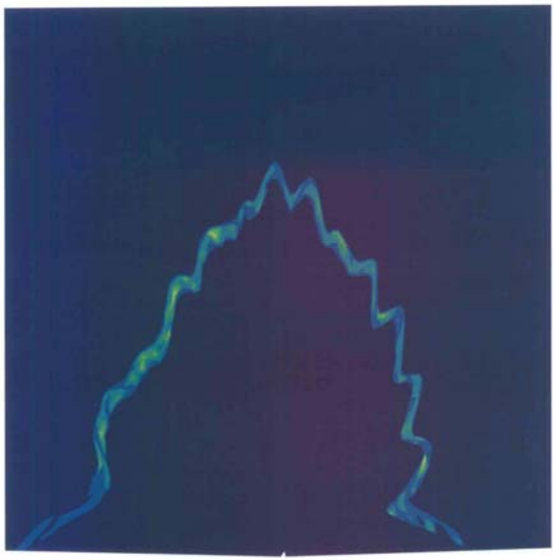
- Detectable signals from ^{21}Ne, ^{79}Br, and ^{127}Xe.
- Product/loaded ratio defined as before.
- Factor of 2 for Ne/O ratio; large factors for Kr/Br and Xe/I ratios.
- Ratios are favorable but overall number of reaction products might be marginally detectable – number of atoms less than 1.0E+6.

	Ratio
$^{21}Ne/^{18}O$	1.94
$^{79}Kr/^{79}Br$	94.1
$^{127}Xe/^{127}I$	82.8

Ice Roughness ^{21}Ne Evolution Failure



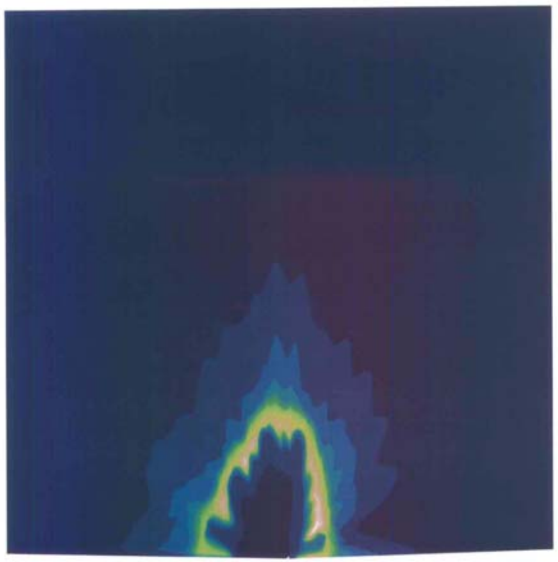
Density



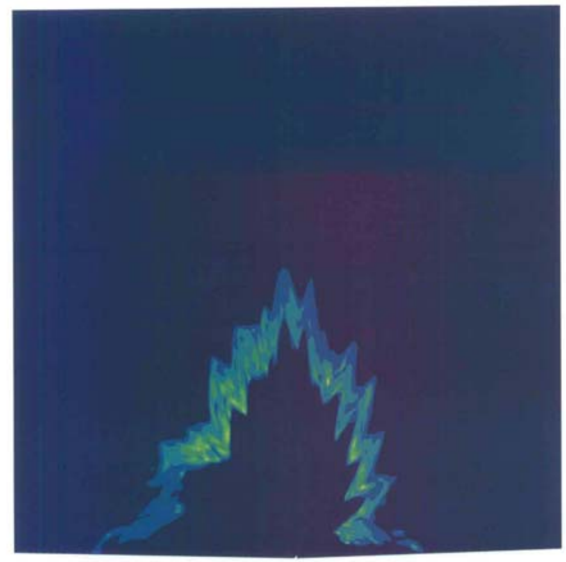
^{21}Ne Abundance

t_{peak} -193 (psec)

Ice Roughness ^{21}Ne Evolution Failure



Density



^{21}Ne Abundance

t_{peak}+70 (psec)

Preliminary Conclusions

- Most extensively studied modes to date are laser drive asymmetries.
  - Sc and Ir have robust, measurable signals and differentiate cases.
  - Near-term collection will include gas handling.
  - Ne, Br and Xe have large, measurable signals.

- Low and high mode instabilities are under investigation.
  - Clear differences in isotopic ratios but absolute abundances are at the detection threshold.